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Development of biogas combustion in combined heat and power generation

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ABSTRACT

Based on the biogas feedstock and its generation cycle, a considerable part of biogas ingradients are noncombustible gases. Low calorific value (LCV) of biogas is one of the most important barriers of biogas development in the combined heat and power (CHP) generation. Biogas purification is usually performed in sensitive utilizations, however modification methods such as cryogenic and membrain are not economic. Therefore, new methods of biogas utilization should be experimented. In this study, characteristics of biogas are investigated under various combustion regimes such as biogas conventional combustion, hydrogen-enriched biogas traditional combustion, biogas flameless mode and hydrogen-enriched biogas flameless combustion. Since biogas conventional combustion is not well-sustained due to LCV of biogas, hydrogen addition to the biogas components could improve combustion stability however NO_x formation increases. Although flameless combustion of fosil fuel have been developed, few documents could be found about biogas flameless mode. Flameless combustion of biogas could be one of the best methods of pure biogas utilization in CHP generation. Combustion stability and low pollutant formation are the main advantages of biogas flameless combustion. The initial cost of flameless combustion instalation is high due to the cost of instrumentation and special equipments. In order to maintain the temperature inside the flameless chamber, some especial materials such as ceramic should be utilized. Biogas flameless combustion could be modified by hydrogen-enrichment strategy. The temperature distribution inside the flameless chamber is more uniform when small amounts of hydrogen added to the biogas components and the flameless regime is more sustained. In this circumstance the rate of pollutant formation is a little higher than pure biogas flameless combustion.

Contents

1. Introduction

Climate change and global warming as the most important greenhouse gases (GHG) effects have become the main concerns of humanity. The negative effects of GHG ingredients such as carbon dioxide (CO_2), methane (CH_4), water vapor (H_2O), nitrous oxide

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(N_2O) and ozone (O_3) on people health are unavoidable fact [1]. Beside these ecological constraints, the increasing rate of nitride oxide (NO_x) emissions should also be controlled in the combustion systems. Since thermal NO_x formation mechanism is responsible for the major part of NO_x formation in the CHP generation systems, flame temperature should be reduced [2]. In industrial point of view, boilers and gas turbines are the most commonly gaseous fuel consumers for CHP generation. Due to Kyoto protocol (KP) stringent standards, great progress has been made to reduce GHG in CHP generation systems by implementation of some strategies such as alternative fuel utilization or clean combustion of fossil fuels using dry low emission techniques, based on lean premixed combustion [3]. In order to approach to the clean environment, both clean fuel and clean combustion technology should be taken into consideration. Biogas generated from organic material can be utilized as an alternative fuel and a source of renewable and sustainable energy in transportation and industrial boilers. In addition to biogas, fertilizer and irrigation water are produced from anaerobic digestion (AD) of organic waste materials. Unlike fossil fuels and other renewable energy resources, biogas generation is not limited to the specific geography. Higher calorific values of biogas can be achieved when methane (CH_4) concentration increases by dioxide carbon (CO_2) elimination from biogas ingredients. Indeed, in the specific utilization such as vehicle fuel, hydrogen sulfide (H_2S) and water vapor should be removed from biogas components due to their corrosive characteristics. Just clean and upgraded biogas is eligible to be applied in sensitive applications such as injection to the gas grid or using as vehicle fuel.

1.1. Environmental panorama of biogas utilization

Energy and fossil fuel consumption are the basis of industrial and economic development. However, increasing rate of GHG generation, climate change and global warming (GW) are the main results of excessive fossil fuel utilization [4]. GHG play crucial roles in GW constitution by trapping heat radiation from the earth's surface [5]. CO_2 and CH_4 are the most important GHGs with 60% and 15% contribution in GW formation [6]. Fossil fuel utilization in transportation systems releases the considerable part of GHGs and biomass has emerged as a savior due to its environmentally sound characteristics [7]. Climate change is one of the most important reasons why governments have been convinced to invest in biomass production. Among different biomass resources, biogas characteristics have made it an acceptable source of renewable energy throughout the world [8]. Indeed, without appropriate strategies for biogas capturing from AD, huge amounts of CO_2 and CH_4 could be released to the environment. Hence, biogas collection from AD not only can provide an acceptable source of energy but also can save the environment from toxic gas emissions [9]. Although high quality of gaseous fuel is not required for CHP generation and biogas can be utilized directly, the corrosive characteristics of water vapor and H_2S as the ingredient of biogas highlights the necessity of biogas cleaning treatments [10]. The presence of H_2S in biogas components could damage CHP equipment in conventional biogas flames and during biogas combustion, it could form sulfur dioxide (SO_2) and sulfur trioxide (SO_3) which are toxic emissions [11].

2. Biogas composition

The process of fossil fuel formation is very slow, taking many years, and current fossil fuel utilization is rapidly depleting the natural reserves. Therefore, many studies have been undertaken to find a variety of renewable fuels to replace these transient fossil fuels [12]. Biogas, which is formed in the AD of biomass, is a renewable and flammable gas with relatively short formation time. The type of AD feedstock plays crucial role in the biogas ingredients [13]. LCV biogas consists of combustible CH_4, noncombustible CO_2 as the basic components and low amounts of nitrogen (N_2), hydrogen sulfide (H_2S), carbon monoxide (CO), ammonia (NH_3), hydrogen (H_2), oxygen (O_2), water vapor (H_2O), dust and occasionally siloxanes [14]. Agricultural products, rice paddies [15], municipal solid waste (MSW) [16], domestic garbage landfills and old waste deposits [17], palm oil mill effluent [7], sewage sludge [18], manure fermentation and cattle ranching [19], coal mining [20] are the most important biogas resources in the world. The digestion process takes place in digestion tanks which allow the possibility of controlling humidity and temperature to optimize biogas generation. Most of the energy content of organic material is transformed to biogas in the AD system and less heat is released. AD process works well when heat is added to the system [21]. Compare to the calorific value of natural gas (36 MJ/m^3), the average calorific value of biogas is very low (around 21.5 MJ/m^3). Due to the various AD feedstock, CH_4 forms around 40–80% of the biogas ingradiants. Therefore, invoking to the lower heating value of CH_4 at the standard temperature and pressure (around 34,300 kj/m^3), the lower heating value of biogas should be around 13,720–27,440 kJ/m^3. Since more than 98% of biogas is a combination of CH_4 and CO_2, the physical properties of biogas are usually modeled by these two gases. Table 1 depicts biogas ingredients based on various feedstock [22].

2.1. Biogas upgrading

In order to remove noncombustible gases from biogas ingredients and increase calorific value of biogas, some upgrading methods such as water scrubbing, cryogenic, chemical absorption technique and membrane have been proposed. Water scrubbing system as a physical biogas purification method is applied to neutralize corrosive gases such as H_2S and to eliminate interfering gases like CO_2 and particulate matter from biogas components due to their higher

Table1
Biogas composition based on different feedstock.

Component	Unit	[a]POME biogas	Sewage plant	Landfill
CH_4	Vol%	60–70	55–65	45–55
CO_2	Vol%	30–40	35–45	30–40
N_2	Vol%	< 1	< 1	5–15
H_2S	ppm	10–2000	10–40	50–300

[a] POME biogas: Biogas released from palm oil mill effluent.

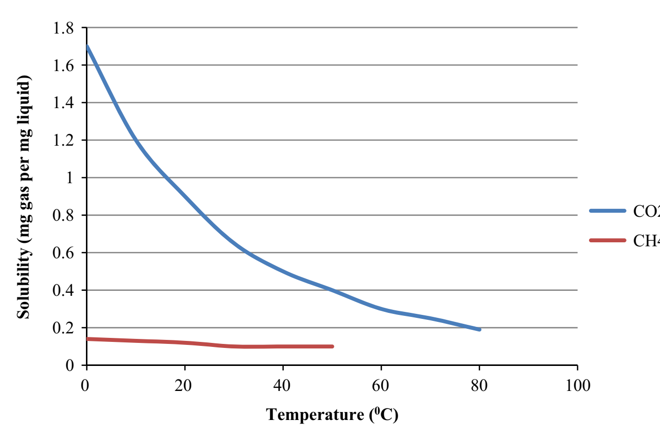

Fig. 1. Solubility of CH_4 and CO_2 in water.

solubility in water compared to CH_4. The solubility of CO_2 in water increases in lower temperatures as shown in Fig. 1 [23].

The absorption process of biogas impurities in water scrubbers is done counter-currently where pressurized biogas is injected to the bottom of the column and water is admitted at the top of the scrubber. Since CH_4 partly dissolves in the water wash process in absorption vessel, the exited water is conducted to the low-pressure flash tank to separate dissolved CH_4. Fig. 2 demonstrates water scrubbing single pass process schematically. The upgraded biogas obtained from the dryer usually contains more than 90% methane. Water scrubbing systems require high amounts of fresh water for biogas impurity absorption especially in single pass scrubbers [24].

In most of the physical biogas upgrading processes, a lack of a specific plan for H_2S collection and its conversion to valuable products is observed. Therefore, a chemical absorption system should be installed to remove H_2S. Since biogas upgrading process is very complicated and in some cases it is very expensive, it is preferred to use pure biogas in CHP generation and do some modifications in biogas combustion step [25,26].

3. Biogas conventional combustion

Although application of biogas could be economic due to waste-to-well characteristic, development of biogas utilization in large scale has been encountered serious problems because of its LCV as well as its corrosive nature. In the last decade, LCV fuels were not taken into consideration in the energy mix of the world due to the abundance of fossil fuels and their low prices. However, irregular utilization of fossil fuels have made some concerns about the future of energy mix of the world, thus recent augmentation of energy prices have attracted more attentions to application of LCV fuel in power generation. Hence, investigation of combustion characteristics of different biogas combinations has been more highlighted. In industrial applications, pure biogas is not eligible to be substituted of liquid petroleum gas (LPG) or natural gas (NG) in commercial burners without any modification. Since CO_2 constitutes considerable part of biogas, the burner orifice pressure intended for NG or LPG is not sufficient to ensure the stability of biogas combustion. Therefore, a new instrument includes a burner and control system should be installed separately for biogas fuel. Indeed, the temperature of the furnace run with biogas fuel should be maintained higher than the dew point temperature to prevent the condensing because H_2S and water vapor as the ingredients of biogas have corrosive characteristics. Thus, the combustion furnace should be heated up by high calorific value (HCV) fuels to achieve higher operating temperature [27]. It implies the necessity of a dual role burner application in biogas conventional combustion systems. To switch over from HCV fuel (such as LPG or NG) to biogas, some instruments should be installed. Therefore, beside LCV of biogas, complicated setting of the traditional biogas combustion systems could disappoint biogas users from biogas

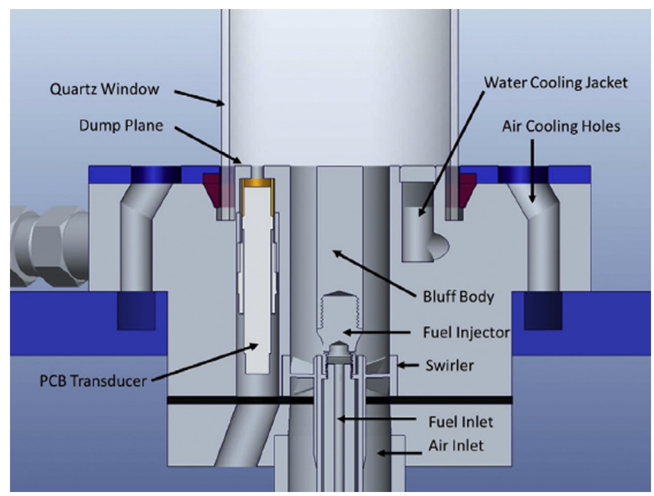

Fig. 3. Cutaway view of combustor fueled by biogas [30].

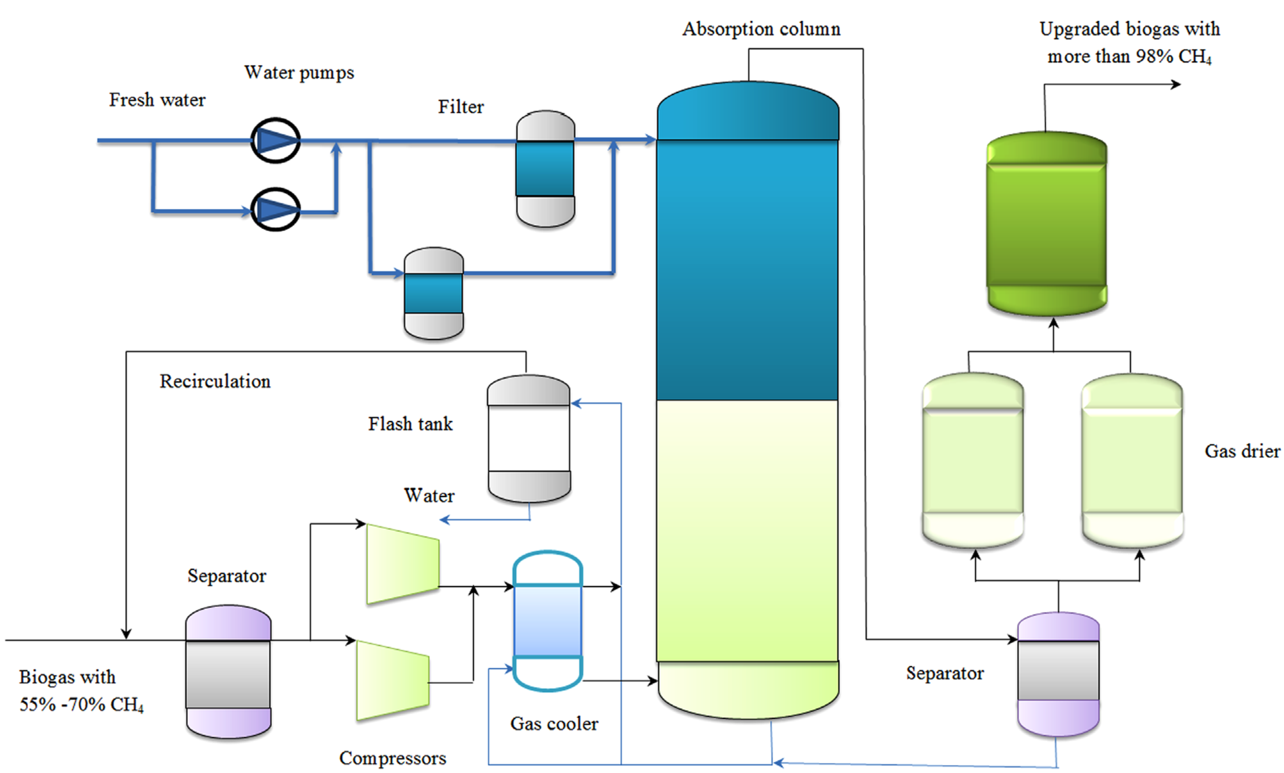

Fig. 2. The schematic of biogas water scrubbing single pass process.

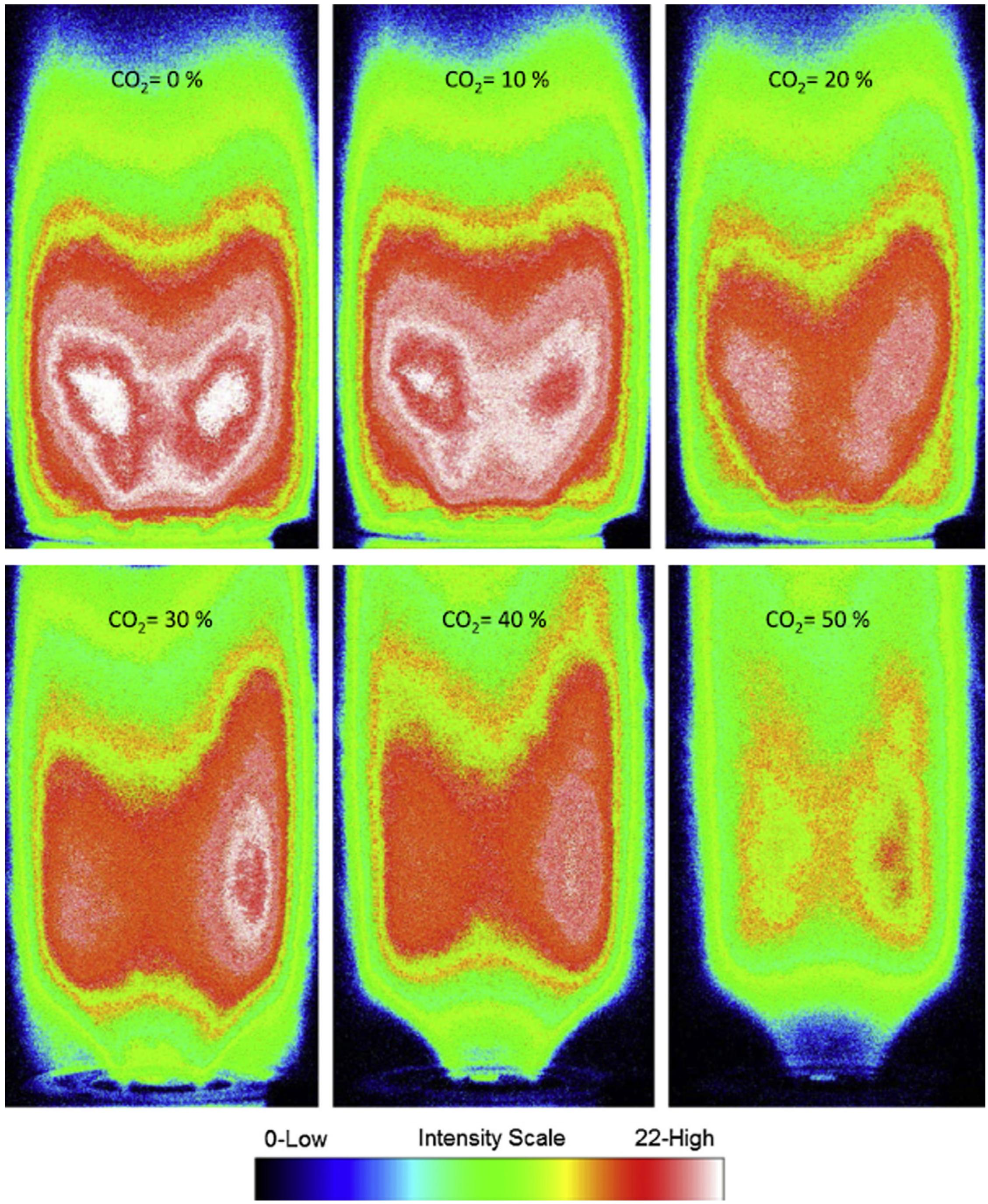

Fig. 4. Biogas conventional combustion with respect to various CO_2 concentrations [30].

utilization [28]. In biogas conventional combustion, the flame velocity plays an important role in the designing of the burner. In order to prevent flame blowing out, the rate of fuel and air to the chamber should be adjusted. Due to the low CH_4 concentration in biogas components, the flame velocity of biogas conventional combustion is lower than NG. Consequently, air and fuel flow rates should be reduced to prevent flame blow out. The maximum flame velocity is achieved at the stoichiometric air to fuel ratio. Due to non-combustible ingredients of biogas, the flame temperature of biogas conventional combustion is lower than NG [29]. Mordaunt et al. [30] studied the effects of some parameters like inlet air temperature, CO_2 doping level and fuel injection configuration on the combustion of biogas in land-based gas turbines shown in Fig. 3.

The authors stipulated that high concentration of CO_2 in biogas components increases CO formation and weakens the flame, effecting the lean-blowout point. The behavior of the flame in various concentration of CO_2 when equivalence ratio is equal to 0.7 is presented in Fig. 4.

Lafay et al. [31] compared combustion stability and flame structure of methane and biogas in a lean gas turbine premixed conventional combustion. The composition of investigated biogas from waste mechanization was 5% N_2, 34% CO_2 and 61% CH_4 by volume [32]. They pointed out that at high equivalence ratios; a stable flame is constituted in both biogas and pure methane conventional combustion. When the equivalence ratio reduces, the flame becomes unstable and low frequency pressure fluctuations were observed. At low equivalence ratios, the flame became

stable again before extinction. Thermal and chemical characteristics of conventional counter-flow diffusion flame of biogas were investigated by Jahangirian et al. [33]. The flame of various combinations of biogas (Flame1: 100% CH_4, Flame2: 40% CO_2+60% CH_4, Flame3: 39% CO_2+61% CH_4 and Flame4: 60% CO_2+40% CH_4) were investigated numerically and experimentally. Fig. 5 shows the combustion characteristics of various biogas blends in terms of peak temperature and pollutant formation. It was stipulated that the net of three GHGs emissions (CO_2, CH_4 and N_2O) decrease significantly in biogas conventional combustion in comparison with pure methane combustion.

Crookes et al. [34] investigated the rate of emission formation in the spark-ignition engines fueled by biogas. It was found that in the combustion of biogas includes noticeable amount of CO_2, the rate of NO_x formation is very low compared to the NG conventional combustion, however un-burnt hydrocarbons (UHC) is higher in biogas conventional combustion. The efficiency of electricity generation from burning biogas in CHP generation systems in large turbines and small generators is 34–40% and 25% respectively [35,36]. The amount of possible electricity which can be converted from biogas in CHP systems is calculated by

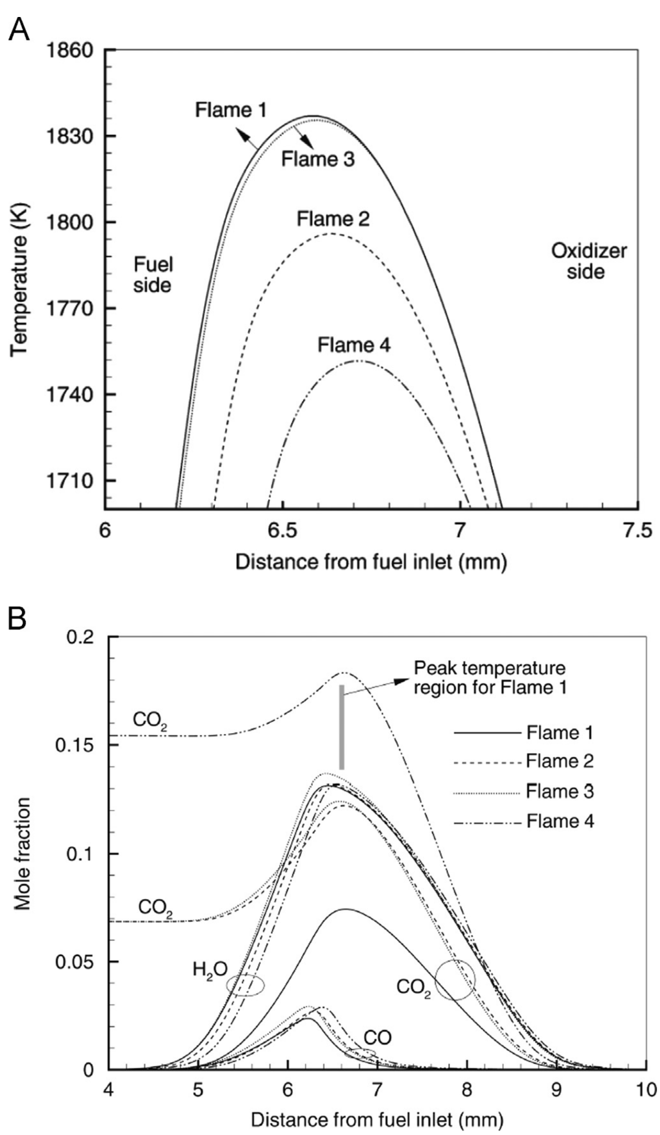

Fig. 5. Combustion characteristics of various biogas blends in terms of (A) peak temperature and (B) pollutant formation [33].

Eq. (1) [37].

$$e_{biogas}[KWh] = E_{biogas}[BTU] \times 0.00293 \left[\frac{KWh}{BTU}\right] \times \eta \quad (1)$$

where e_{biogas} is the total generated electricity from biogas, E_{biogas} represents the unconverted raw energy in the biogas and η is the overall conversion efficiency.

4. Hydrogen-enriched biogas conventional combustion

Hydrogen (H_2) has great potential to be applied as an environmentally friendly alternative fuel with low CO_2, sulfur oxide (SO_x), UHC, CO emissions in combustion process [38]. Due to diffusivity and high flammability, the explosion risk in storage and transportion of pure H_2 is very high and safty insurance during utilization of pure H_2 is one the main concerns [39]. Hence, hydrogen enrichment of various gaseous fuel like CH_4, propane (C_3H_8) and NG has been developed in recent decades, however the impacts of hydrogen enrichment on biogas traditional combustion has not been well-developed. Since biogas has been known as one of the valuable and avilable alternative fuels in the world, hydrogen-enriched biogas combustion stability and pollutant formation could be an atractive topic in combustion field. The raised temperature as well as quick reaction rate with O_2 due to H_2 combustion can ensure the fuel saving targets under the radical development method [40,41]. Combustion characteristics of a spark ignited single cylinder engine fueled by hydrogen-enriched biogas with various ratios of hydrogen (15%, 20%, 25%, 30%, 35% in volume) were investigated by Zahang et al. [42]. It was concluded that hydrogen fraction enhancement in the biogas components leads to the acceleration of the rate of heat release from combustion system. Indeed, the flame development angle decreases due to dominant effects of the chemical reaction. Also, the stability of engine performance could be ensured by higher hydrogen fraction in the biogas blends. Park et. al. [43] evaluated the performance of a spark ignition engine fueled by hydrogen-enriched biogas using exhaust gas recirculation (EGR) method. The experimental results confirm that the EGR system has lower impact on the fuel economy when less than 20% H_2 is injected to biogas. In further H_2 blending ratios, EGR method illustrates higher performance with lower NO_x formation compared to the legal standard. In this study, the authors proposed a spark gap further into the combustion chamber with EGR system to enhance the engine efficiency and improve the combustion characteristics. Zhen et al. [44] experimented the effect of hydrogen enrichement on the stability of biogas diffusion flames. The corresponding changes were found in the appearance of the biogas flame when the rate of additional hydrogen was verified from 5% to 10%. The authors reported that the stability of biogas flame increases significantly when just 5% hydrogen is added to the biogas components.

5. Biogas flameless combustion

LCV of biogas and the expensive process of cleaning and upgrading of biogas are the most important barriers of biogas utilization development in CHP generation. These two disadvantages of biogas could be eliminated by using flameless combustion technology. Flameless regime can be sustained in extremely LCV fuel conditions and elimination of CO_2 from biogases is not necessary [45]. Flameless combustion which is known as Low NO_x Emission Injection or Colorless Distributed Combustion (CDC) in the US [46], Low oxygen Dilution (MILD) combustion in Italy [47], High Temperature Air Combustion (HiTAC) in Japan [48] and Flameless Oxidation (FLOX) in Germany [49] is a promising combustion technology to decrease

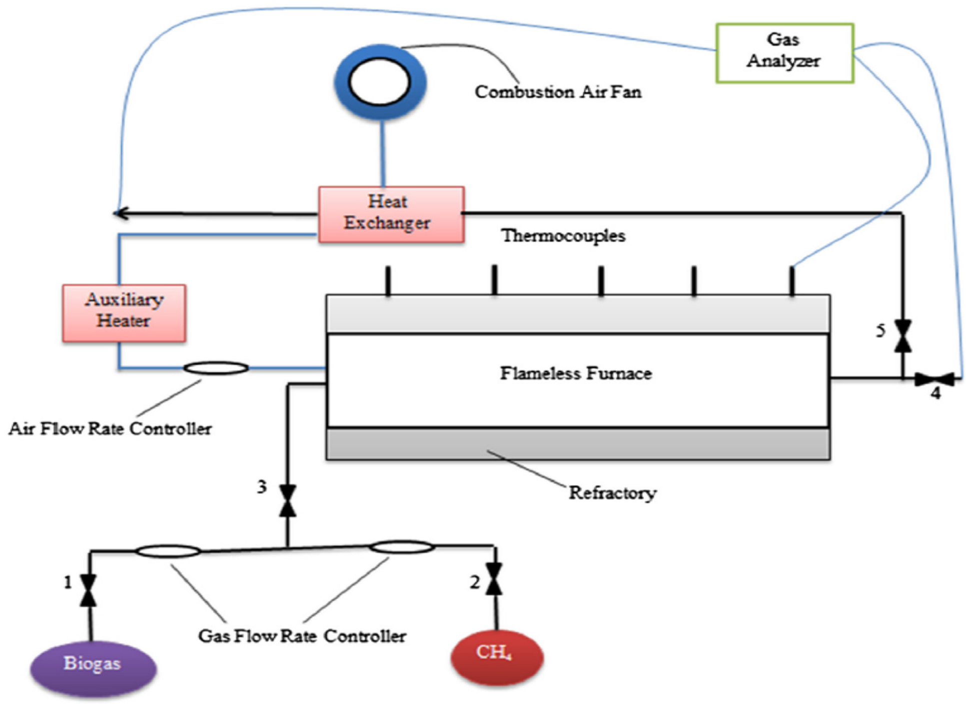

Fig. 6. Experimental set up for biogas flameless combustion [66].

emission formation in combustion phenomenon and simultaneously to generate high efficiency in CHP systems. Flameless combustion technique could be appropriate for industries where a homogenous temperature distribution within the chamber is required [50]. Flameless combustion of gasous fuel has been applied successfully in steel making, cement industries and glass making factories [50,51], industrial boilers [52] and gas turbines [53]. In gasous fuel flameless combustion, gas and highly diluted air react at the temperatures over the auto-ignition temperature of the fuel. In this conditions, flame could not be stable and lifts off [54]. Flameless combustion regime could be sustained when diluted air injected into the chamber at exteremely high velocities [55], thus low amount of oxygen concentration and high Reynolds number of oxidizer disappear the flame [56]. Although flameless combustion of gaseous fuel such as methane, propane and natural gas has been noticed [57–61], biogas flameless combustion has not been developed properly [62]. Effuggi et al. [63] experimented biogas flameless combustion and pointed out that the stability of flameless is related to the recirculation ratio (k_v). As long as the amounts of k_v is less than 7.3 and greater than 3, biogas flameless region could be observed. To obtain appropriate recirculation ratio, an appropriate diameter of the fuel nozzle should be designed based on the Strong Jet Weak Jet (SJWJ) theory [64]. Colorado et al. [65] stipulated that the efficiency of biogas flameless combustion is 2% lower than natural flameless mode. Since in biogas case, the density of CO_2 is higher than natural gas, heat capacity, absorption and radiation properties are higher. Danon et al. [62] studied the pollutant formation of LCV fuel flameless combustion in a gas turbine system experimentally and numerically. Ultra low emission was reported in terms of NO_x formation and CO_2 constitution. Hosseini et al. [66,67] studied biogas flameless combustion experimentally and numerically. Fig. 6 shows the related experimental set up.

Practically, in order to achieve biogas flameless mode, th furnace should be heated up and the temperature with in the chamber should be increased to the temperatures over the auto-ignition of biogas. It was reported that biogas is not eligible to be utilized in the heating step and it is necessary to use a HCV fuel such as methane. The needed enthalpy for biogas self-ignition temperature is supplied by enthalpy of preheated air. It was reported that in biogas flameless mode, the mean temperature of the chamber is lower than biogas conventional combustion. Uniform temperature inside the chamber during flameless combustion is one of the most advantages due to NO_x emission suppression and entropy generation minimization. The rate of exergy loss in biogas conventional combustion in conventional combustion of biogas compared to the biogas flameless mode. In chemical reaction setting of numerical approach, Damköhler number should be taken into consideration.

6. Hydrogen enriched biogas flameless combustion

Although various characteristics of hydrogen-enriched gaseous fuel flameless combustion have been investigated experimentally and numerically [68–74], few documents could be found about hydrogen-enriched biogas flameless mode. Flameless combustion of biogas could be sustain when hydrogen is added to the biogas ingredients because of very high heating value of hydrogen and also laminar flame speed and adiabatic flame temperature of hydrogen [75]. Parente et al. [76] investigated flameless regime fueled by hydrogen-enriched gaseous fuel numerically and experimentally. It was claimed that for capturing the volumetric features of flameless combustion of hydrogen-enriched gaseous fuel, the detailed chemistry approach should be developed. Chen and Zhen [77] investigated hydrogen-enriched biogas flameless combustion in counter-flow configuration. The effects of hydrogen concentration of biogas mixtures on the biogas flameless structure were studied with the aid of the lattice Boltzmann method (LBM). Indeed, the effects of some parameters such as the oxidizer preheated temperature and the rate of oxygen concentration in the oxidizer flow were considered. The authors concluded that flameless oxy-fuel biogas combustion could be sustained when small amount hydrogen added to the biogas components. In addition, low preheated temperature of the oxidizer and diluted oxygen concentration in the oxidizer could respond the challenges of CO_2 emissions.

7. Conclusion

Although biogas is an available renewable and sustainable source of energy, LCV of biogas is one of the most important barriers of biogas utilization development in the CHP generation systems. Since biogas upgrading technologies such as membrane and cryogenic are not economic, new combustion methods should be experimented to find the best methods for biogas utilization. In this regard, characteristics of biogas conventional combustion were studied. The stability of biogas traditional flame is not sufficient to be considered as a fuel in CHP generation systems. In order to improve the efficiency of biogas conventional combustion, hydrogen-enriched biogas conventional combustion was proposed. Although stability of flame is higher in this case, pollutant formation increases. Flameless combustion technique has been proposed as the best combustion method for biogas utilization in CHP generation. Biogas flameless mode could be sustained even in high CO_2 concentrations. The uniform temperature inside the flameless chamber could ensure the durability of the refractory. Since accurate instrumentation and a specific refractory (such as ceramic) should be installed in flameless combustor, the initial cost of this method is high; however, corrosive nature of biogas (due to present of H_2S) cannot damage the chamber. Hydrogen addition to the ingredient of biogas in flameless combustion regime increases the combustion stability but pollutant formation intensifies.

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